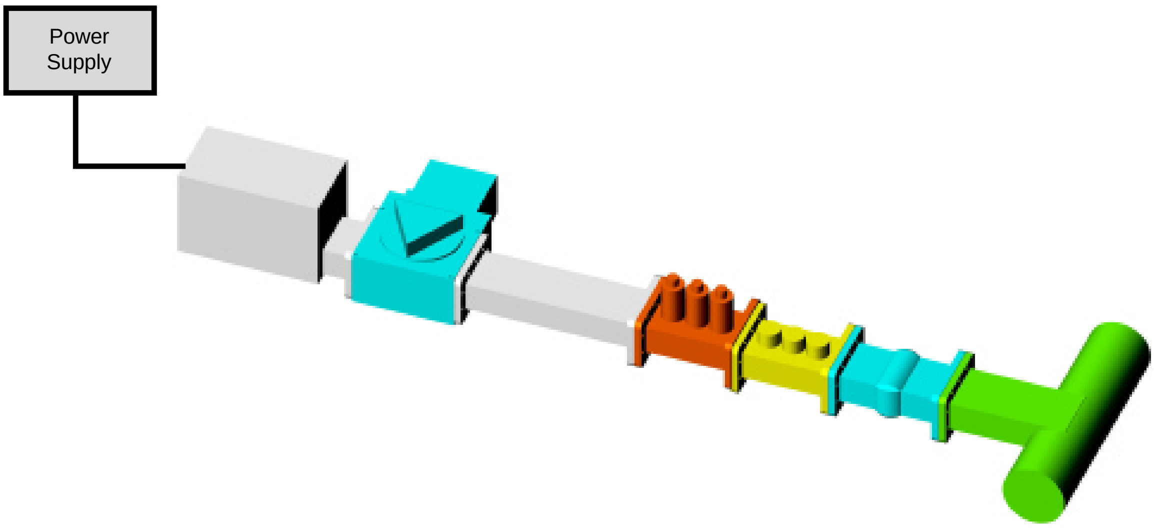
A GUIDE FOR

MICROWAVE APPLICATION



Introduction

This booklet is intended to give a general introduction for processing engineers that intend to apply microwaves in their installation. It addresses in particular those users of microwave systems that want to treat unconventional goods and for that reason do not want to buy standard turn key units from one single supplier.
In a compressed way the reader shall find basic knowledge about microwave installations which otherwise is tedious to be found in textbooks. It is not the intention of the authors to make a consulting microwave engineer obsolete but we would like to give an impression:

- which decision a processing engineer will have to make when thinking of using microwaves
- which choices are strongly restricting further options
- which are vulnerable points of his system
- where can he save costs and maintenance expenses

Reading this booklet should enable a processing engineer to save effort, time and money by becoming aware of problems, risks and traps and to know when he should ask a consultant before he binds himself by a wrong decision.

Frequency

The authors limit themselves to the most commonly used industrial scientific, and medical (ISM) frequency of 2.45 GHz, despite the authors have designed and built components at 915 MHz that in some countries also is an ISM frequency and also worked at much higher frequencies in the range of the ISM frequency of 24 GHz and higher. To work in this high frequency range several modifications of the installation have to be made which will not be discussed here.

Microwave Generator

Tube

All types of microwave generators have more or less the same configuration. They consist of an electron emitting cathode that provides an electron beam, a vacuum section where the interaction between the electron beam and the electromagnetic field takes place, a collector where the spent electron beam is dumped and a window where the generated microwaves leave the tube for the users purpose.

To interact with the electromagnetic field in the said interaction region the electrons have to satisfy conditions like surfers on waves in the sea. This means they have to propagate with the same speed as the wavefront does. Since surfers want to be accelerated by the wave they have to keep in front of the crest of the wave. In a microwave tube the electrons behave inversely. They do not obtain but transfer energy to the wave by propagating behind the crest. Thus the task of a the tube engineer is to take care that the speed of the wave front is as fast as the electron beam and that the electrons propagate a bunch behind the crest of the wave and remain in synchronism at this relative position as they propagate through the interaction space. Dependent on the principles used to achieve this task and dependent on the speed and direction of the wave fronts the tubes are called klystrons, travelling wave tubes (TWT), backward wave oscillator (BWO), magnetrons or gyrotrons.

Even though the authors have designed and manufactured complicated components of tubes we will not discuss these different principles here but will give advice how to choose and reasonably apply them for the desired purpose.

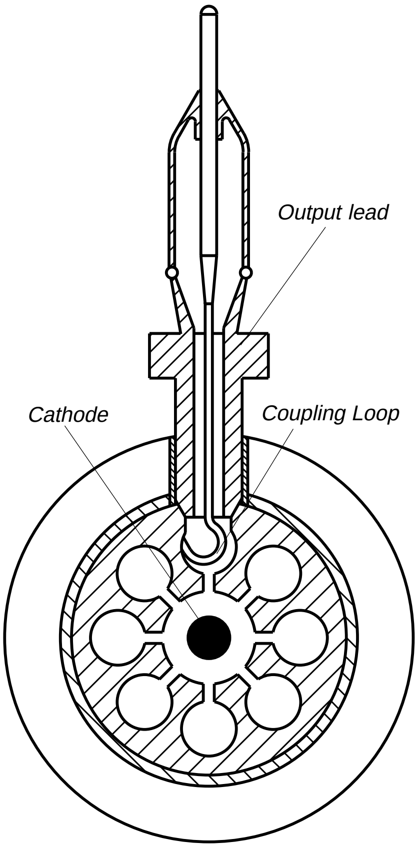
- Who has ever watched surfers can understand how difficult the tube engineer’s design work is to have the electrons bunched at the right position and in synchronism with the wave. It becomes clear that any perturbation of the wave field in the tube will not only significantly drop the tubes performance but also jeopardize the tube itself. A reflection of the microwave power from the load or transmission line components of about 1 % may already cause the end of the lifetime of the tube.

- To have an electron beam accelerated to velocities comparable to the wave front velocity DC accelerating voltages as high as a few kW have to be provided by means of special power supplies. The requirements given by the tube designer are severe and the power supplies are often more than twice as expensive as the tube itself.

- There are tubes where the electron beam is guided by means of a time constant magnetic field. Dependent on its generation by means of permanent magnets or electromagnets they may need an additional power supply, however with considerably reduced requirements.

- If the oscillation frequency is only determined by the tube’s parameters it is called oscillator. If the tube needs an input signal it is called amplifier. Gyrotrons and magnetrons are oscillators whereas klystrons and TWTs are amplifiers. For radar, communication and accelerator applications amplifiers are applied. They are also of advantage if - for the process - the frequency has to be swept over a certain range, however for industrial microwave processing purposes oscillators are preferred which saves the cost of the generator for the input signal.

- Almost all tubes applied for processing purposes are magnetrons. A cross section can be seen in the figure below. They are usually not ordered directly from a tube manufacturer but from the manufacturer of the power supply who knows the requirements of the tube. Typically they very roughly cost about 2 - 3 DM/W.



Cross Section of a Magnetron

A much cheaper method some processors do is to buy a stack of kitchen microwave ovens take out the magnetron and its power supply and trash the rest of it. For some purposes this is quite a reasonable approach, however the drawbacks at least have to be known. They will be discussed below.

Power supply

The microwave generators have to be supplied by means of power supplies that transform the 230 V 50 Hz net voltage to the required DC high voltage of a few kW. They can be separated in switch mode power supplies (S.M.P) and conventional supplies based on 50 Hz technology. The conventional supplies are considerably cheaper however their drawbacks make it advisable to apply SMPs. SMPs have much lower weight, less stored energy and guarantee a much higher lifetime of the tube than the conventional supplies. They are now available in power ranges up to several tenth of kW.
Most power supplies obtain an analogous low voltage signal from a control unit.
The lifetime of the magnetron partly depends on the features of the power supply especially if the magnetron output power has to be varied. The supplier of the tube specifies operating curves for controlling the output power. If these curves can not be followed by the supply the magnetron may jump into unfavorable modes leading to a damage of the tube. Before buying an expensive system a consultant should be contacted. It also is advisable to buy the power supply and the tube from the same supplier. This allows the manufacturer of the power supply to take into consideration the impedance characteristic of the tube.

Launcher

Between the coaxial output coupler of a tube and the rectangular standard waveguide there must be a transition section called a launcher. It is optimized by the tube manufacturer and usually bought together with the tube. Transversel forces on the launcher often restrict the arrangement of the tube. Before the technical construction is made a consultant should be asked.

Transmission Lines

Basic Theory

Electromagnetic energy propagates in rectangular waveguides in the form of transverse electric TE_{mn} or transverse magnetic TM_{mn} modes. In our case only TE_{mn} modes are considered, since the launchers are optimized for these modes. The integer numbers m and n indicate the number of the maxima the mode has in the two transverse directions perpendicular to the waveguide axis. To specify a TE_{mn} mode all combinations of the integers m and n are allowed except m=n=0.

Waveguide modes can be decomposed into plane waves that propagate at the Brillouin angle relative to the axis. This angle is calculated by means of the wave propagation vectors. For the waveguide axis parallel to the z-direction we obtain for the two transverse wavenumbers:

$$k_x = m \pi / a \ ; \ k_y = n \pi / b$$

where a and b are the width and height of the waveguide. For the axial wavenumber we have:

$$k_z = (k^2 - k_x^2 - k_y^2)^{0.5} \quad (1)$$

where

$$k = 2 \pi / \lambda$$

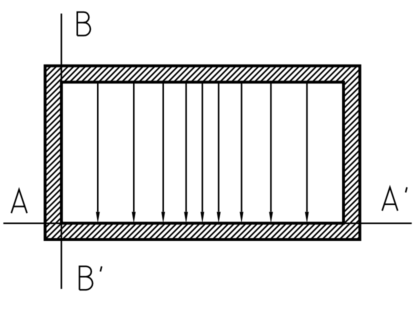
is called wavenumber. The axial dependence of a field component of a mode can be expressed as:

$$f(z) = \exp(i \, k_z \, z)$$

where i is the imaginary unit. For each of these modes there is a frequency and hence a wavenumber where in eq.(1) the argument of the square root becomes negative and hence k_z becomes imaginary. The corresponding frequency is called cutoff frequency. Below this frequency no propagation of this respective mode is possible. As the indices of the modes rise their cutoff frequency rises as well. Hence the lowest order modes TE_{10} or TE_{01} have the lowest cutoff frequency.

Modes with one index equal to zero have no maximum and hence no variation of amplitude in one direction transverse to the axis. For these modes the cutoff frequency only is determined by the size of that side where the maxima and minima occur. Hence for a waveguide of rectangular but not squared cross section the TE_{10} and TE_{01} mode have different cutoff frequencies which has the consequence that for a waveguide of rectangular cross-section there is a frequency band where only one mode is above cutoff. For this frequency band the waveguide of rectangular cross section is called a monomode waveguide. Dependent which side transverse to the axis is larger the fundamental mode is called TE_{10} or TE_{01} mode. For the square cross section these modes have identical cutoff frequencies and for that reason they are called to be degenerate.

The electric field lines of the TE_{10} can be seen in the following figure. In the horizontal direction there is one maximum and in the vertical direction there is a uniform field distribution.



From these considerations it can be understood that at a given frequency a minimum size of one side of the rectangular waveguide is required to have the lowest order mode above cutoff. This minimum size is half the wavelength of the electromagnetic power. For a frequency of 2.45 GHz this minimum size is 61.2 mm. By means of the axial wavenumber a waveguide wavelength can be calculated to be:

$$\lambda_H = 2 * \pi / k_z \quad (2)$$

As modes propagate along the waveguide their phase varies according to their waveguide wavelength which is different from the so called free space wavelength λ determined by the ratio of the velocity of light to the frequency. As can be seen from the equations (1) and (2) at the cutoff frequency the waveguide wavelength is infinitely long and shrinks in length with increasing frequency and at frequencies high above cutoff it asymptotically drops to the free space wavelength.

The R-26 waveguide is the standard monomode waveguide for transportation of microwave power at the ISM frequency of 2.45 GHz. It has a cross section of 86.36 mm x 43.18 mm where only the fundamental TE_{10} mode can propagate. The guide wavelength is about 170 mm. This is true for air or vacuum filled waveguides. If the waveguide is filled by a dielectric with the dielectric constant ε the cutoff frequency rises and the waveguide wavelength shrinks with the square root of ε.

Description of Waveguide Components

For most of the components the process engineer does not need to have detailed knowledge about their design and inner field distribution, however needs to know the behavior at their intersection to the outer world, called ports. In particular he needs to know the response at all the ports when a mode of given amplitude is incident into one port. This is achieved by means of a scattering matrix formalism. For a given mode each matrix element S_{mn} describes the wave amplitude that appears at port n when the respective mode with unit amplitude is incident into port m. For example a waveguide monomode section has for its two ports the scattering matrix (absolute value) :

$$|S| = \begin{bmatrix} |S_{11}| & |S_{12}| \\ |S_{21}| & |S_{22}| \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

which means that for the respective mode incident at port 1 there will be a wave of the same amplitude at port 2 ($|S_{12}| = 1$) and no reflected wave at port 1 ($|S_{11}| = 0$). The same is true for a mode launched from the other port. The overall scattering matrix of groups of elements can be calculated by means of cascading the individual scattering matrices. Microwave engineers that act as consultants for microwave processing companies have these programs available.

Isolator

The isolator serves as a protection of the magnetron against microwave power reflection from the load or transmission line components. It has three ports where by means of ferrites the power incident into one port is directed into the second port and the power incident into the second port is directed into the third port. Port 1 of the isolator is connected to the magnetron, port 2 is connected to the transmission line and port 3 is connected to a matched load. The power launched from the magnetron is directed to the transmission line, however the power reflected from the line is directed to the matched load. At the matched load it is advisable to have a detector that gives a signal proportional to the power reflected from the transmission line into the load. The scattering matrix (absolute values) of an ideal isolator is:

$$S = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

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Obviously an ideal matched load has one port only and the single element scattering matrix is

$$S = S_{11} = 0$$

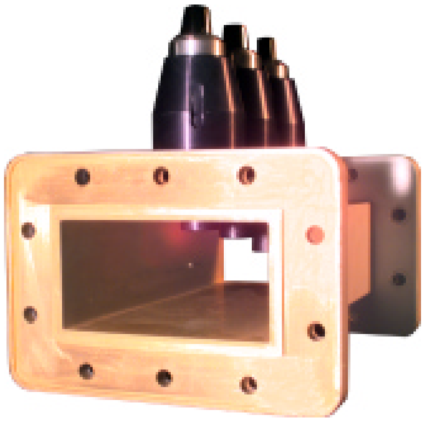
The ideal isolator together with the ideal matched load (port 3 closed by the load) has for the remaining two ports the overall scattering matrix:

$$S = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$$

If the isolator is bought from a different supplier than the microwave sources it is recommended to compare the scattering matrix of the isolator to the requirement given by the tube.
Due to the need of ferrites and the required reliability isolators are expensive. They often cost as much as the tube itself. Most suppliers of power supplies and tubes also offer isolators that often they buy from elsewhere and resale with some profit. It is advised to ask a consultant whether cheaper options can be found elsewhere.

Tuner

The tuner serves as a matching element between the applicator and the generator unit. By driving the tuning stubs into the waveguide artificial obstacles leading to partial power reflection are obtained. The amplitude of the reflected signal depends on the depth the tuning stubs are moved into the waveguide. The phase of the reflected signal depends on the location of the moved stub. Usually these tuners are delivered with three tuning stubs located along one wavelength.
When moving the stubs into the waveguide the operator changes the scattering matrix of this individual unit such that the overall scattering matrix - cascaded of the applicator and the tuner - reduces to one element such that $S = S_{11} = 0$.



3-StubTuner for R-26 Waveguides

Knowing the scattering matrix of the tuner for each position of the tuning stubs and measuring the reflection coefficient from the applicator allows calculation the optimum position of the stubs. Controlled motor driven tuners are available and - especially compared to installations with moderate power - quite expensive. For that reason in most cases we recommend first studying the oven behavior by tuning the stubs and watching the reflected signal at the isolator load. This makes the decision easier whether the investment of a measurement system and a motor driven tuner pays off.

Compared to most other components mechanically driven tuners are fairly cheap and the price does not strongly depend on the supplier.
It should be emphasized that a tuner only reduces the reflection of the power back into the transmission line. However, it will not necessarily improve the behavior of the applicator. On the contrary for a poorly designed applicator trapped resonances may be caused that jeopardize the applicator installation. If absorption of the power is low a consultant should be asked instead of endangering the system. Trapped resonances can be detected by means of a directional coupler.

Directional coupler

A directional coupler serves to measure the forward and backward propagating power. Dependent on the frequency it consists of

- two parallel waveguides with are coupled by an array of holes where a fraction of the power propagating in the waveguide is coupled into the second waveguide serving as diagnostic guide
- coupling holes with antennas along one waveguide wavelength

For the standard R-26 waveguides they can be bought by several suppliers. For larger sizes they have to be built by specialized companies like us, the RM company.

Bend

Often the geometrical restrictions make it necessary to use bends. They have to be designed such that the reflection back into the waveguide is low. For the standard R-26 waveguide these bends are commercially available from several producers.

One distinguishes between H- and E- plane bends. For H-bends the waveguide is turned around the line B-B', see figure in "Basic Theory". For E - bends they are turned around the line A-A'.

Twist

Waveguide twists are used if because of geometrical restrictions it is necessary to turn the waveguide 90 degrees around its axis. At the RM company these twists are available for sizes where they can not be obtained by commercial suppliers.

Window

For some processes a special atmosphere and hence microwave permissible windows are required. Dependent on the required window material by means of a scattering matrix formalism the optimum thickness of the window can be calculated by a consultant. In most cases he optimizes the window for one mode and one frequency.

Windows for a larger frequency band can be designed as well however the mode always has to be well defined.

Complete Systems

The structure of a complete system can be seen in the figure on the right. All components have been described in the upper text.

As mentioned above there are users that use generators taken form kitchen microwave ovens. They have the problem that they do not have a launcher that efficiently excites the TE_{10} mode in a R-26 standard waveguide.

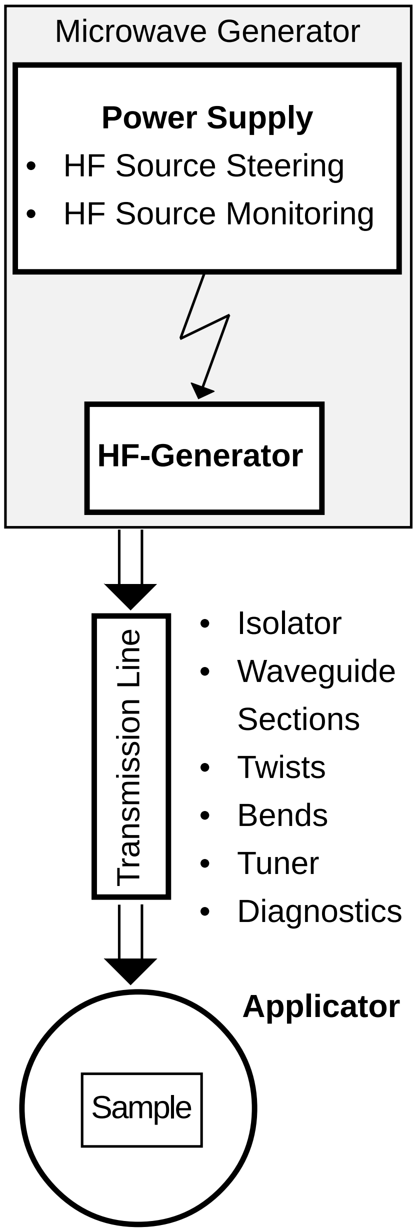
This means they can not use the transmission line elements described above, especially no isolator. These microwave units often are flanged directly to the applicator. This saves a lot of money however the question is:

How often do the magnetrons have to be replaced due to failure?

There is an immediate but often not very helpful answer:

No isolator is necessary if in time average the reflection from the load is lower than specified by the tube supplier, i.e. if the scattering matrix element S_{11} of the load is below the allowed threshold.

The difficulty is to find out whether this is the case. An answer to this question never is obvious and can either be found in experiment or detailed calculations. It is highly recommended to ask a consultant before starting with an own detailed investigation.



About the Authors

Arnold Möbius received his diploma degree from the University of Karlsruhe in electrical engineering.

Starting at the KFK Karlsruhe (now Forschungszentrum Karlsruhe FZK), in the early stage of his career he has been deligated to the Massachusetts Institute of Technology. In the beginning of 1990 he founded his own engineering and consultant office that at the beginning of 1993 was added by IMT GmbH. Founded as Spin off company IMT acts as distributor for solid state semiconductors and also in close cooperation with us, the RM company, IMT provides waveguide components at frequencies of 915 GHz up to 200 GHz. A. Möbius acts as consultant for several companies that have interest in using microwaves in their production. Some customers obtained exclusive rights for particular products.

Running the company in the third generation, Markus Mühleisen is head of the Reinhold Mühleisen GmbH since 1995 . RM is designing and producing specialized microwave components for frequencies ranging from 945 MHz up to 200 GHz. Complete systems have been build for 2.45 GHz for industrial application and higher frequencies e.g. 30 GHz and 170 GHz for research purposes.

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